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# Are challenging walking environments linked to falls or risk of falling in children with cerebral palsy? A systematic review

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ABSTRACT

*Background:* Children with cerebral palsy (CP) regularly fall over and this has negative effects on their physical and psychosocial wellbeing (e.g., reduced activity participation). However, the reasons for falls are not well understood. The way in which children negotiate challenging walking environments (e.g., uneven surfaces), may reveal more about how falls occur as these environments require gait modifications to maintain stability. Stability in challenging walking environments has been explored for children with CP; however, it remains unclear how these lead to falls.
*Research question:* Do challenging walking environments that mimic those faced in the real-world, contribute to increased fall occurrence and fall risk in children with CP?
*Methods:* Five databases were searched, and 1386 records screened to include ambulatory children with CP, aged 5–18 years old, investigating dynamic walking in challenging environments, with outcomes of fall occurrence or fall risk. The full protocol for this review was registered on PROSPERO (CRD42021290456).
*Results:* Sixteen studies met the inclusion criteria. One study reported occurrence of stumbles, two reported no falls. Fifteen studies identified gait alterations used by children with CP in challenging environments. Twenty-four gait characteristics were identified to be indicative of cautious walking strategies and seven gait characteristics identified to increase fall risk, suggesting a potential link. However, limited evidence exists as to whether this reflects falls faced in the real-world.
*Significance:* Investigations into stability over challenging walking environments for children with CP are lacking any measures of fall occurrence. Investigations into the mechanisms that may contribute to high fall risk, or fall avoidance when negotiating obstacles, uneven surfaces, steep declines and stairs may reveal further causes of real-world falls, and in doing so inform future fall prevention techniques. Finally, understanding the multifaceted causes of falls in real-world challenging environments from the perspectives of children with CP is key for future research.

## 1. Introduction

Cerebral palsy (CP) is a complex neuro-musculo-skeletal disorder and a common cause of motor impairment [1]. Children with CP often experience issues with balance and coordination; 35 % report daily falls and a further 30 % report weekly or monthly falls [2]. Previous work recognizes both the physical consequences of falls (e.g. head injury) [3], and that falls can increase feelings of embarrassment and frustration for children with CP, especially in adolescence where social pressures are high [4]. This leads to reduced social and physical participation [5–7]. It is acknowledged that most young children fall, regardless of impairment [8]. From five years of age, typically developing (TD) children show greater stability in their gait patterns compared to children with CP [9] and fall less. With reduced stability, children with CP continue to fall throughout childhood and into adulthood thus impacting overall well-being [4,10].

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Fall prevention requires anticipatory mechanisms as well as proactive and reactive control to maintain the centre of mass (COM) within the base of support (BOS). During locomotion this can be described as maintaining dynamic stability [11]. Research on the epidemiology of falls in TD children in the real-world is well documented [3,12,13], but understanding of the mechanisms that contribute to real-world falls in children with CP is limited. Children with CP have demonstrated greater instability compared to TD children during walking [14], suggested to be due to associated gait characteristics including smaller knee flexion-extension range of motion (ROM) [15] or in-toeing of the foot [2]. However, Boyer and Patterson [2], evidenced that gait characteristics typically expected to increase falls in children with CP (e.g. in-toeing, scissor gait), were not associated with real-world fall frequency according to falls history. Children with CP have also shown a more cautious approach to gait over level ground compared to TD children with compensatory mechanisms to maintain stability, for example increasing step width, which increases BOS and therefore improves dynamic stability [16–18]. Despite this, it is not fully understood whether compensatory strategies increase or decrease real-world falls in children with CP.

A lack of understanding about where and how falls occur in children with CP is likely in part due to investigations of stability taking place over level surfaces in most experimental studies and clinical gait analysis. In the real-world, children will often encounter and must negotiate challenging natural and built environments such as uneven surfaces (e.g. on the walk to school). Walking in a laboratory over level ground does not consider these real-world challenging environments that might increase fall risk and thus cannot truly reflect how kinematics are adjusted during more advanced balance challenges that are encountered day-to-day [19,20].

Challenging environments are defined here as places that require additional adjustments to gait characteristics for maintaining stability, and successful negotiation (preventing a fall) due to difficulty imposed by the surrounding natural or built environment compared to level walking. Examples include encountering unseen obstacles (e.g. branches, kerbs), uneven surfaces (e.g. cobble stones, uneven grass) or places with restricted foot placement or foot contact with the ground (e.g. narrow paths, stairs), which require adjustments to gait characteristics such as greater step width to increase stability or higher foot clearance to prevent tripping [20]. Falls, particularly in the anterior direction, may be more likely in the presence of a challenging environment that causes a perturbation [17]. Impairments associated with CP may additionally make the required adjustment to avoid a fall within these environments difficult [1]. It is plausible that changes to gait characteristics (spatio-temporal parameters, trunk and lower limb kinematics and various measures of stability) in challenging environments may be good indicators of fall risk in children with CP. Challenging environments have been used to assess some gait characteristics, including dynamic stability of children with CP previously [19–26]; however direct links to everyday fall risk and fall rates remain unclear. Moreover, the necessity for further investigation specifically into fall risk and the impact of challenging environments on gait in children with CP has been highlighted in a recent review [15].

Understanding reasons for real-world falls in children with CP that occur day-to-day, where challenging environments are common, is an important step to reduce negative physical and psycho-social consequences of falls. Evidence exists that children with CP experience regular falls [2,27], but understanding where these falls occur and the effect of challenging environments on fall risk is unclear. This systematic review aimed to (1) synthesise existing knowledge on whether challenging environments contribute to fall occurrence in children with CP and (2) establish whether any specific gait characteristics demonstrated by children (spatial-temporal parameters, kinematics, stability measures) compensate for or contribute to instability and increased fall risk, specifically when children with CP negotiate challenging environments.

## 2. Methods

This systematic review protocol was carried out following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), guidelines [28]. The protocol for this review was registered with PROSPERO (CRD42021290456).

### 2.1. Search strategy

Five electronic databases (Web of Science, PubMed, Scopus, CINAHL and MEDLINE) were searched using specific search terms defined by the study's Population, Exposure, Comparator, Outcomes, Study Design (PECOS) framework (Table 1). Searches were carried out on the 6th December 2021, then re-run on the 5th May 2022, 11th October 2022, 3rd May 2023 and 13th September 2024 to check for any new publications. Search strings and key words were carefully selected to ensure a comprehensive search by discussion of the study PECOS and inclusion firstly of any word relating to ambulatory children with CP (e.g. hemiplegi*), then any word relating to real-world challenging environments (e.g. incline, uneven) and finally any word relating to falls or stability (e.g. trip, balance). These terms were tailored for each database (supplementary material 1). Reference lists of eligible studies were additionally searched. Searches had no restriction on country or year of publication but were restricted to full text articles written in English language.

### 2.2. Screening and selection process

Duplicates were removed in EndNote™ X9 [29]. Remaining studies were imported into Rayyan© [30], a freely usable systematic review software for screening research articles, where two researchers (RW, RF) independently reviewed titles and abstracts, according to inclusion and exclusion criteria (Table 2).

Full text studies were screened with inclusion and exclusion criteria. Final studies were included for data extraction, synthesis and quality assessment and grouped according to challenging environment.

### 2.3. Quality assessment

The National Institute of Health (NIH) quality assessment tool [31] was used to assess quality and internal validity of included studies and determine any risk of bias. This was assessed according to study type (e.g. observational or intervention). The NIH quality assessment tool allows assessment of study design, methods and implementation using 14 individual questions in which a response of "yes", "no" or "could not determine" was awarded by two independent reviewers. Two reviewers (RW, RF) each reached a decision on quality rating of each included study (good, fair or poor) using NIH guidance. Any disagreements were discussed and resolved by both reviewers after each separately

**Table 1**
PECOS for systematic review study design.

| PECOS | Description |
|---|---|
| **Participant** | Ambulatory children with cerebral palsy (5–18 years old) with a gross motor function classification system level I to level III and the ability to walk without walking aids. |
| **Exposure** | Challenging walking environments: defined as real-world or laboratory settings in which additional gait difficulties are induced by surrounding external features within that environment (e.g. uneven surfaces, obstacles), that have been designed to replicate daily challenges to gait that occur in the natural or built environment. |
| **Comparison** | Typically developing children to children with cerebral palsy<br>Level walking compared to challenging environments. |
| **Outcome** | Fall occurrence and fall risk. |
| **Study Design** | Peer-reviewed original articles. Observational or intervention studies. |

**Table 2**
Inclusion and exclusion criteria.

| Inclusion Criteria | Exclusion Criteria |
|---|---|
| • English, full text, all years, all countries<br>• Peer-reviewed original research articles<br>• Involvement of ambulatory children or adolescents with CP<br>• Observational studies assessing gait between children with CP and TD children and baseline data from intervention studies (if applicable)<br>• Studies involving dynamic walking<br>• Studies involving walking in challenging environments designed to replicate daily walking experiences other than typical level overground walking (e.g. obstacles, uneven ground, incline walking)<br>• Outcome measures of fall rates or fall risk as measured by associated gait characteristics (e.g. dynamic stability) | • Reviews (literature or systematic), books, theses, congress proceedings, letters to editors, qualitative studies<br>• Studies including adults over 18 years of age and children under the age of 5 years<br>• Studies not including children or adolescents with CP, or that focus only on children with CP with Gross Motor Function Classification System (GMFCS) level IV-V or who are non-ambulant (cannot walk without walking aids)<br>• Assessment of TD children alone or level overground walking alone (without comparison to patient population or exposure of interest)<br>• Any challenge to gait other than natural or built environmental features and topography, for example activities during walking that are initiated by children not due to environmental constraints (e.g. dual-tasking, running, turning) or any standing or sitting postural tasks |

completing another quality assessment and determining an agreed score.

### 2.4. Data extraction

Two reviewers (RW, RF) carried out data extraction using a shared data extraction table in Microsoft Excel [32], which was discussed with all members of the review team (TOB, GB, BC).

Data extraction included: study title, authors, year, study type (observational or intervention), definition of falls or near-falls, number of participants, participant demographics (age, clinical diagnosis, GMFCS level), study methodology (involvement of challenging walking environments, assessment tool) and study outcomes.

Study outcomes included: number of falls or near-falls, and measures indicative of fall risk: spatial-temporal parameters (walking speed, step length, step width, cadence, single and double support time), margin of stability, COM movement, feelings of stability and kinematics (joint angles, ROM, foot clearance). Measures of central tendency (median, mean, standard deviation and range) were extracted.

### 2.5. Data synthesis

Narrative synthesis was chosen for this review. Studies needed to be arranged into homogenous groups depending on the challenging environment investigated, thus narrative synthesis allowed textual comparison within and between challenging environments. The data extraction table was used to assess study characteristics and group studies according to type of challenging environment (e.g. uneven surfaces), since gait characteristics associated with fall risk (e.g. foot clearance) could not be compared between different environments. Fall occurrence was synthesized using descriptive measures of central tendency of number of falls or near-falls recorded in each study. Fall risk was grouped according to associated gait characteristics (e.g. kinematics), then synthesized according to descriptive measures of central tendency (means, standard deviations, range, and median scores).

During narrative synthesis, data from children with CP were compared to TD children when negotiating the same challenging environment, but comparison across different tasks was not possible for fall risk. Data were summarised firstly by study characteristics, then by fall occurrence, then by fall risk characteristics for each environment. Findings were visualised in the data extraction table, then data synthesis was checked by all members of the review team.

## 3. Results

### 3.1. Study characteristics

A total of 1386 studies were screened following removal of duplicates (Fig. 1). Full text screening was completed on 34 studies, 1 could not be retrieved and 17 were excluded, leaving 16 studies included in the review following all searches. A summary of included studies is shown in supplementary material 2, all were published between 2002 and 2024.

Five challenging environments were investigated across all studies, these were: uneven surfaces (n = 4) [19,22,26,33]; incline/decline walking (n = 7) [23–25,34–37]; obstacle crossing (n = 4) [20,21,33,38]; treadmill perturbations (n = 1) [39] and stairs (n = 1) [40]. One study investigated two challenging environments (uneven surfaces and obstacle crossing) before and after a 4-week exercise intervention [33]. Thirteen out of 16 studies were cross-sectional or case-control designs [19–26,35–37,39], three studies were interventions from which baseline data were extracted [33,38,40].

All studies included children with CP between the ages of 5 and 18 years who could walk independently (GMFCS I and II), except one study with children with spastic diplegia that did not specify GMFCS [21]. Four studies included only children with hemiplegia [26,34,37,40], six studies included only children with diplegia [21–24,35,36]. Sample sizes of children with CP across studies ranged from 10 [23,25,36] to 46 [33], all including similar numbers of TD children, apart from Bailes et al. [38], Coman et al. [33], Choi et al. [34] and Camuncoli et al. [37], who only included children with CP.

Within studies of uneven surfaces utilized polyurethane plastic squares moulded to create an uneven walkway of 6 m [26] or 7 m length [22], or bags of 0.5 cm pebbles placed at various positions over a 1.5 m x 0.4 m area [19,33]. Incline walking was measured on a treadmill at 5° [34], 7° [35] or 10° [25,34] slope, and on fixed ramps of 7° [23,36] or 5° and 10° [24] slopes.

Five studies measured both incline and decline walking, on either 5°, 7° or 10° slopes [23,24,34,36,37]. Four studies conducted incline or decline walking barefoot [23,25,35,36], one study conducted incline and decline walking outside with shoes [23] and two studies conducted incline and decline walking inside with shoes on a fixed ramp [24] or a treadmill [34]. One study conducted incline and decline walking in an interactive environment on an instrumented treadmill with different types of ankle-foot orthoses (AFOs) [37].

Obstacle crossing was assessed by stepping over a fixed hurdle height of either 10 cm [20] or 23 cm [33] or over obstacles of various heights (0 %, 10 % and 20 % leg length) [21], and all hurdles were made using cylindrical sticks placed on two vertical stands. One study observed obstacle crossing performance using the standardized walking obstacle course (SWOC) [38], a test designed to measure stability and speed of gait over a number of different surfaces and challenges (three directional turns, stepping over a crutch placed on the floor, walking over various surfaces and sit-to-stand activities) [41].

One study investigated treadmill perturbations within a virtual reality environment by applying posterior split belt treadmill accelerations at three different walking speeds (0.5, 0.8 and 1 m/s) [39]. One study assessed stair negotiation, which analysed stepping up and down four steps (rise: 15.2 cm, run: 24.1 cm) both with and without AFOs [40].

### 3.2. Fall occurrence

Three studies identified presence or absence of a fall or near-fall within a challenging environment [20,38,39]. One recorded stumbles as part of the SWOC test and found that children with CP stumble 0.27

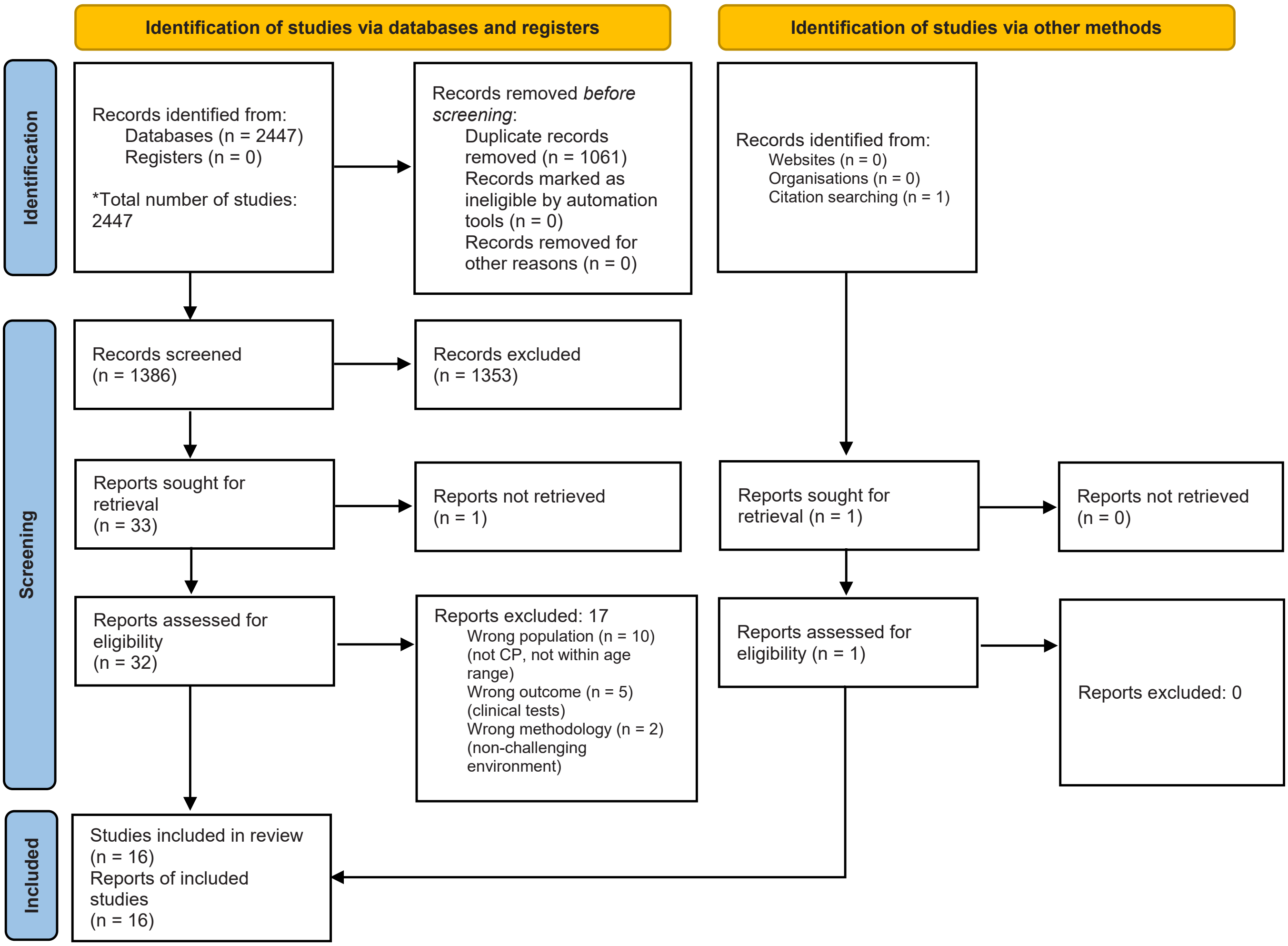


**Fig. 1.** PRISMA flow diagram [41]. *Total number of studies (before duplicate removal): 2447 (Web of Science: 960, PubMed: 442, Scopus: 913, MEDLINE: 92, CINAHL: 40).

times per attempt at the SWOC [38], and two (obstacle crossing [20] and treadmill perturbations [39]) stated that no falls occurred during the challenging task or that the task was completed successfully. All studies that included a fall occurrence measurement [20,38,39], did not state whether the challenging environment of interest increased fall occurrence or fall risk.

One study [38] defined a stumble as having contact with obstacles on the SWOC but no other studies out of 16 provided a definition for a fall or near-fall. Thirteen studies did not measure fall occurrence [19,21–26,33–37,40], four of which did not include ‘falls’ or a derivative of near-falls (e.g. ‘stumble’) within text [33,35–37].

### 3.3. Fall risk

Fourteen studies assessed gait characteristics using three-dimensional (3D) motion capture [19–22,24–26,33–37,39,40], one study used two-dimensional (2D) motion capture [23]. One study assessed obstacle crossing observationally using measures determined by the SWOC test (e.g. time to complete SWOC, number of steps taken, number of stumbles and steps on and off SWOC path) [38]. In all studies except one [23], children with CP were assessed by walking over challenging environments in laboratory settings. All 15 studies that used 2D or 3D motion capture [19–26,33–37,39,40] identified gait alterations in children with CP in response to a challenging environment compared to level walking.

All extracted gait characteristics (n = 52) for each challenging environment can be seen in Table 3, with contributing studies, quality assessment score and comparison to TD children and level ground. This table shows which studies have reported similar gait characteristics in children with CP when walking over challenging environments, in comparison to level ground or TD children. All challenging environments except treadmill perturbations [39] and decline walking [23,24,34,36,37] reported a reduction in walking speed. All challenging environments showed increased step width in children with CP compared to TD children. The narrative synthesis of findings identified several gait characteristics in Table 3, that were suggested by authors of included studies to either be indicative of cautious walking strategies, or potentially increase fall risk over each challenging environment (Figs. 2A and 2B). Fig. 2A shows gait characteristics suggested to be cautious across multiple environments e.g. increased foot clearance over obstacles, which will reduce the likelihood of the foot coming into contact with an obstacle during swing phase. The largest number of cautious strategies were during decline walking. Fig. 2B shows characteristics that were suggested to potentially increase fall risk across multiple environments e.g. reduced ankle dorsi-flexion on uneven surfaces might increase the risk of a trip from the toes making contact with the surface during swing phase. Fall risk characteristics (Fig. 2B) were less common than those suggested to be cautious (Fig. 2A) and were only suggested during obstacle crossing, walking on uneven surfaces and during incline or decline walking, none of which shared the same fall risk characteristics.

**Table 3**
Outcomes of included studies relating to fall risk, measured by associated gait characteristics (kinematics, spatial-temporal parameters). In order of total number of articles offering the same finding, grouped into quality rating.

| Challenging environment | Reported gait characteristics | | | |
|---|---|---|---|---|
| | Finding | Contributing articles | | |
| | | NIH Quality Assessment Score | | |
| | | Good | Fair | Poor |
| Uneven surface | ↓ Walking speed[ab] | [19][ab], [22][ab] | [26][ab], [33][b] | |
| | ↓ Step length[a] | [19], | [26] | |
| | No change in step length[b] | [22] | | |
| | ↑ Hip flexion[b] | | | |
| | ↑ Knee flexion[ab] | [19][ab], [22][ab] | [26][b] | |
| | ↓ Cadence[b] | [22] | [26] | |
| | ↑ Step width[ab]* | | | |
| | ↑ Foot clearance[ab] | | | |
| | Smaller ↑ ankle dorsiflexion (on uneven surface)[a] | | | |
| | ↑ Anterior pelvic tilt[b] | [19], [22] | | |
| | ↓ Internal foot rotation[b] | [22] | | |
| | ↑ Double support time[b] | | [26] | |
| | ↑ Elbow flexion[b] | | | |
| | ↑ Medial COM[a] | | | |
| | ↑ Sagittal pelvis ROM[b] | | [33] | |
| | ↑ Sagittal trunk ROM[b] | | | |
| | Similar frontal trunk ROM[b] | | | |
| | Similar transverse trunk ROM[b] | | | |
| | Similar dorsiflexion ROM[b] | [19] | | |
| | ↑ Hip abduction[a] | | | |
| | ↑ Frontal pelvis ROM[a] | | | |
| | ↓ Frontal pelvis ROM[b] | | | |
| | ↑ Transverse pelvis ROM[b] | | | |
| | ↑ Sagittal trunk ROM[a] | | | |
| | ↓ Frontal trunk ROM[b] | | | |
| | ↑ Transverse trunk ROM[a] | | | |
| | ↓ Sagittal COM to COP inclination angle[a] | | | |
| | ↓ Separation of COM-COP[a] | | | |
| | ↓ Max velocity of COM[ab] | | | |
| Gradient Walking *Inclines* | ↓ Walking speed[ab] | [24][a] | [23][a], [25][ab], [35][a] | [36][a] |
| | ↓ Stride length (level and inclines)[a] | | | |
| | ↑ Hip flexion[b] | [24], [34], [37] | [23], [25], [35] | [36] |
| | ↑ Knee flexion at IC[ab] | [34][b], [37][b] | [23][ab], [25][b], [35][ab] | [36][b] |
| | ↑ Forward trunk lean[ab] | [37][b] | [23][ab], [25][b] | [36][a] |
| | ↑ Dorsiflexion (stance)[b] | [24], [34], [37] | [25], [35] | |
| | ↑ Anterior pelvic tilt[ab] | [37][b] | [25][ab], | [36][a] |
| | ↓ Cadence[ab] | [24][ab] | | [36][b] |
| | Similar stride length[b] | | [23] | |
| | ↑ Step length (affected side only)[b] | [34], [37] | | |
| | ↓ Foot clearance[a] | | | [36] |
| | ↑ Stride width[a] | | | |
| | ↑ Stance phase duration[ab] | | [25] | |
| | ↑ Dorsiflexion (swing)[ab] | | | |
| | ↓ Plantarflexion (swing)[ab] | | | |
| | ↓ Knee flexion (swing)[ab] | | | |
| | ↓ Hip abduction (swing)[b] | | | |
| | ↓ Frontal pelvis ROM[b] | | | |
| | ↓ Transverse trunk ROM[ab] | | | |
| | ↓ Sagittal COM-COP separation | | | |
| | ↓ Dorsiflexion (swing)[b] | | [35] | |
| | ↑ Foot contact (with treadmill belt)[b] | | | |
| | ↑ Forefoot contacts (larger inclines)[a] | [24] | | |
| | ↑ Sagittal pelvis ROM[a] | | | |
| | ↑ Sagittal trunk ROM[a] | | | |
| | ↑ Frontal trunk ROM[ab] | | | |
| *Declines* | ↓ Stride length[ab] | [24][ab], [34][b] | [23][ab] | [36][a] |
| | ↑ Hip extension at IC[ab] | [24][b] | [23][ab] | [36][b] |
| | ↑ Plantarflexion at IC[ab] | [24][b], [34][b] | | [36][a] |
| | ↑ Walking speed[b] | | [23] | |
| | ↑ Dorsiflexion at IC[a] | | | |
| | ↑ Knee flexion at IC[a] | | | |
| | ↑ Trunk extension at IC[a] | | | |
| | Similar sagittal trunk, knee, hip, ankle angles at midstance[a] | | | |
| | Similar walking speed[b] | [24] | | |
| | ↑ Cadence[ab] | | | |
| | ↑ Forefoot contacts with secondary heel touch (larger inclines)[b] | | | |
| | ↓ Sagittal ankle ROM[b] | | | |
| | ↑ Sagittal knee ROM[b] | | | |
| | ↓ Knee flexion at IC[b] | | | |
| | ↓ Sagittal hip ROM[b] | | | |
| | ↓ Frontal trunk ROM[b] | | | |
| | ↓ Stance phase duration[b] | [34], [37] | | |
| *Inclines and declines* | Similar knee flexion (swing)[a] | | | [36] |
| | ↓ Feelings of safety (10° ramp)[ab] | [24] | | |
| | ↑ Focus | | | |
| | ↓ Talking | | | |
| | ↑ Gaze at ground (10° ramp)[ab] | | | |
| Obstacle | ↓ Walking speed[ab] | [20][a] | [33][b] | [21][ab] |
| | ↑ Step width[a] | [20] | | [21] |
| | ↓ Step length (trail limb)[a] | | | |
| | ↑ Foot clearance over obstacle[a] | | | |
| | ↓ Foot clearance over higher obstacle (compared to low)[a] | | | [21] |
| | ↑ Variability of foot clearance[a] | | | |
| | ↓ Stance phase time[b] | | [33] | |
| | ↑ Trunk ROM (sagittal, transverse, frontal)[b] | | | |
| | Similar step length[a] | [20] | | |
| | Similar single support time[a] | | | |
| | ↓ Dorsiflexion (swing)[a] | | | |
| | Similar ↑ knee flexion over obstacle[a] | | | |
| | Similar ↑ hip flexion over obstacle[a] | | | |
| | ↑ Hip flexion (trail limb) over obstacle[a] | | | |
| | ↑ Hip abduction (swing)[a] | | | |
| | ↑ Sagittal pelvis ROM[a] | | | |
| | ↑ Frontal pelvis ROM[a] | | | |
| | ↑ Sagittal trunk ROM (trail limb crossing)[a] | | | |
| | ↑ Frontal trunk ROM | | | |

(*continued on next page*)

Table 3 (*continued*)

| Challenging environment | Reported gait characteristics: Finding | Contributing articles – NIH Quality Assessment Score: Good | Fair | Poor |
|---|---|---|---|---|
| | (lead limb crossing)[a] | | | |
| | ↑ Transverse trunk ROM[a] | | | |
| | Similar sagittal COM-COP inclination angle[a] | | | |
| | Similar frontal COM-COP inclination angle[a] | | | |
| | ↓ COM velocity (lead limb toe-off)[a] | | | |
| Treadmill perturbation | Similar gait pattern[b] | | [39] | |
| | ↓ Stance phase duration[b] | | | |
| | Same number of recovery strides[a] | | | |
| | ↑ Dorsiflexion for CP and TD[b] | | | |
| | ↑ Knee flexion for CP and TD[b] | | | |
| Stairs | ↓ Speed of stair ambulation[a] | [40] | | |
| | Similar single support % (ascent)(involved limb)[a] | | | |
| | ↓ Single support % (descent) (involved limb)[a] | | | |
| | ↑ Single support % (ascent and descent) (non-involved)[a] | | | |
| | Plantarflexion at IC (ascent and descent) (barefoot)[a] | | | |
| | ↓ Dorsiflexion (ascent) (barefoot)[a] | | | |
| | ↓ Knee flexion (swing) (ascent)[a] | | | |
| | ↑ Dorsiflexion at IC with AFO (ascent and descent) | | | |
| | ↑ Foot clearance with AFO | | | |
| | ↓ Sagittal ankle ROM (descent) (barefoot)[a] | | | |
| | ↑ Knee flexion (descent) (barefoot)[a] | | | |
| | ↑ Foot contact and stair ambulation with AFO | | | |

[a] = compared to TD children,
[b] = compared to level ground, ↑ = increase, ↓ = decrease, IC = initial contact, AFO = ankle-foot orthoses, ROM = range of motion

### 3.4. Quality scores

Final quality scores are shown in Table 3. Eight studies were rated as 'Good' [19,20,22,24,34,37,38,40], six studies as 'Fair' [23,25,26,33,35,39] and two studies rated as 'Poor' [21,36]. Studies were typically rated as fair because they did not include a sample size justification [23,25,26,35,39] or did not meet the sample size required to reach statistical power based on earlier calculations [33]. Additionally, several studies did not report details on how participants were recruited [23,25,26,35,39]. Two studies were rated as 'Poor', due to lack of reporting of the method of determining exposure (cerebral palsy diagnosis) [21,36] and for one there was no clear reporting of inclusion and exclusion criteria and no sample size justification [21].

## 4. Discussion

This is the first systematic review to investigate the effect of challenging walking environments on fall occurrence and fall risk in children with CP. Sixteen studies were included, with three [20,38,39] reporting the occurrence or absence of a fall. This primary finding demonstrates that the link between challenging environments and the causes of real-world falls experienced by children with CP is understudied. All studies reported the effect of challenging environments on gait characteristics that could indicate a risk of falling. All but one [38] evidenced at least one example of cautious behaviour when negotiating a challenging environment. The detailed findings of this systematic review are discussed in two parts: the contribution of challenging environments to increased fall occurrence in children with CP; and whether gait characteristics compensate for or contribute to instability and fall risk within challenging environments in children with CP. Gait characteristics are discussed within context for the five different challenging environments identified (uneven surfaces [19,22,26,33], incline/decline walking [23–25,34–37], obstacle crossing [20,21,33,38], treadmill perturbations [39] and stairs [40]).

### 4.1. The link between challenging environments and real-world fall occurrence

This review highlights the limited number of studies reporting fall occurrence as a primary outcome measure when assessing children with CP walking in challenging environments. One study revealed that children with CP stumble once in every four attempts during a SWOC test [38], which might imply increased fall risk in challenging environments; however, stumble locations on the SWOC were not reported so it is unclear whether any near-fall incidences occur due to an obstacle, a change in walking direction or an uneven surface, making it difficult to determine the potential causes/mechanisms of the near-fall. Moreover, the SWOC assessment was used as part of a wider intervention study and was not a comparison to TD children for the purpose of understanding fall risk or fall occurrence. Therefore, it is difficult to determine whether the SWOC test indicates a high fall occurrence or fall risk in children with CP. Despite this, the SWOC test is clearly able to highlight stumbles or near-falls in more challenging environments than level-ground. Thus, with improved reporting, the SWOC test is a potential avenue for clinical assessments of children who might be at higher fall risk in the real-world.

The focus of included studies within this review was on stability and fall avoidance strategies, rather than whether a fall is likely to occur in a particular challenging environment [21–23,25,33,35,36,40]. Consequently, only one study [38] provided a definition of a near-fall, which did not align to standard definitions of a fall or near-fall as it was tailored to specific study methods (defined as contact with obstacles on the SWOC). A fall is described by the World Health Organization (WHO) [8] as "an event which results in a person coming to rest inadvertently on the ground or floor or other lower level". Near falls, sometimes referred to as trips or stumbles, have been defined by Maidan et al. [42] as "a stumble event or loss of balance that would result in a fall if sufficient recovery mechanisms were not in place" [p.646]. Several studies included in this review aimed to identify how balance and stability is affected in challenging environments [19,20,24,26]. Yet, without knowing if falls occur in these environments, it is difficult to determine whether any instabilities typically lead to real-world falls or whether suggested gait compensations, used to maintain stability, are successful for preventing falls in these environments day-to-day. A suggestion for future work is to not only improve reporting and consideration of real-world fall occurrence but to also adopt standardized terminology for a 'fall' and 'near-fall' to allow consistency in reporting between studies.

### 4.2. The link between challenging environments, gait characteristics and fall risk

Although gait characteristics were identified in six studies which were assumed to be linked to fall risk [20–22,24,26,33] (Fig. 2B), the link demonstrating that these factors do contribute to real-world falls was not proven. Children with CP adopt cautious behaviours over

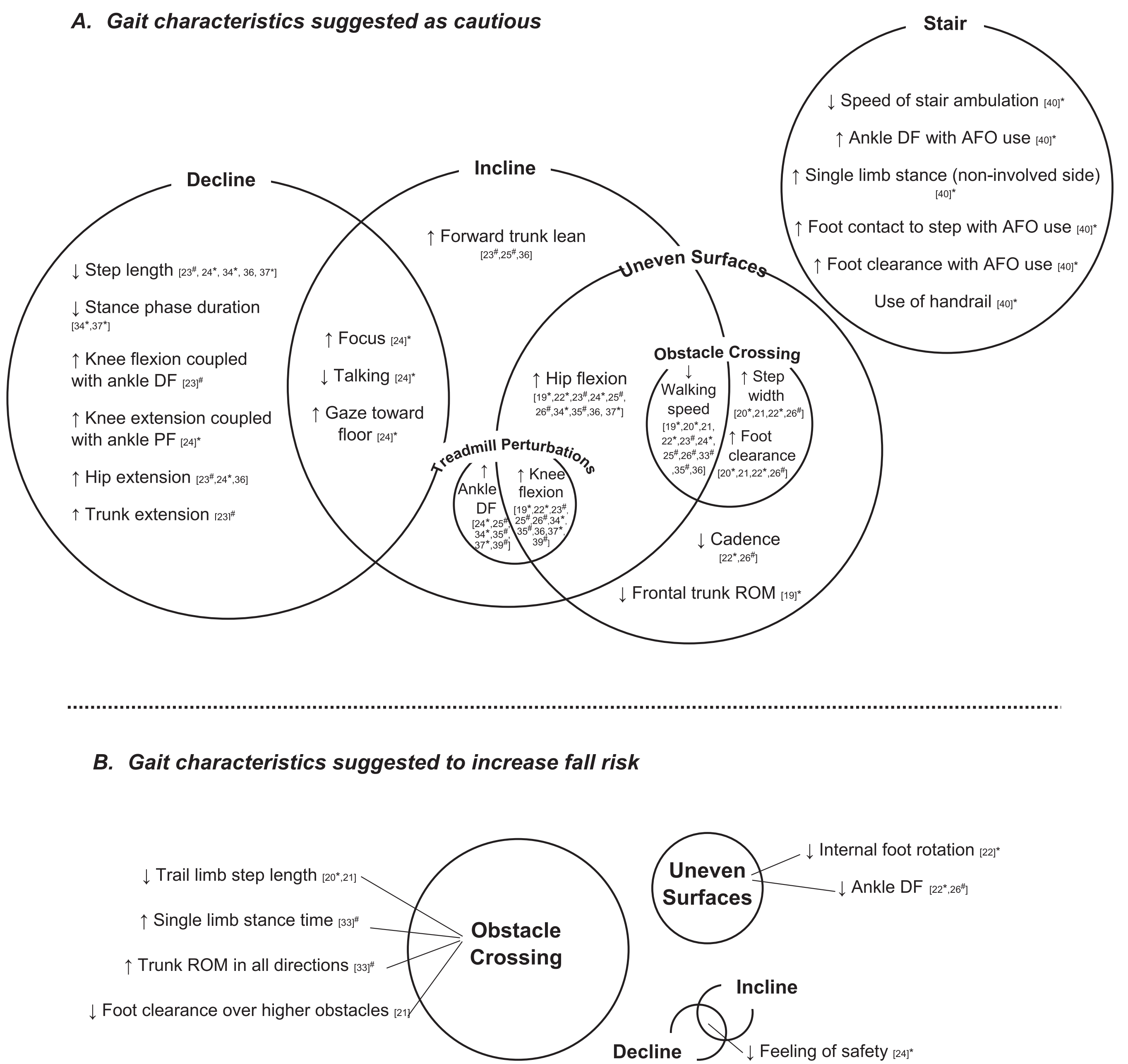


**Fig. 2.** Synthesis of gait characteristics identified in each challenging environment that were suggested by included papers to evidence (**A**) cautious behaviour to maintain stability or (**B**) increased fall risk. Size of circle (diameter in cm), scaled to number of characteristics, e.g., 8 cautious behaviour characteristics for declines = 8 cm. Overlapping circles represent gait characteristics identified within two or more separate challenging environments from separate studies e.g., increased hip flexion is a cautious behaviour used by children identified in a study investigating incline walking and a separate study investigating uneven surfaces. [] = reference to papers in which the gait characteristic was identified, * = Good, # = fair quality assessment score. DF = dorsiflexion, PF = plantarflexion, TD = typically developing children, ↓ = decreased, ↑ = increased.

challenging environments to maintain stability by reducing walking speed and widening the BOS, making it easier to keep the COM within the BOS. Similar differences can be seen over level ground in children with CP [15]. Further investigation is required to determine whether the same cautious behaviours reported in laboratory environments occur in real-world challenging environments.

(a) Uneven surfaces

Children with CP exhibited cautious strategies, reflected by a number of changes to gait characteristics when walking on uneven surfaces compared to level ground, including reduced walking speed [19,22,26,33], increased step width [22,26], reduced cadence [22,26], and increased foot clearance [19,22,26] aided predominately by increased knee flexion [22,26], but also by increased hip flexion [22,26]. These changes were suggested as compensatory mechanisms to prevent instability due to the uneven surface. One study reported significantly reduced frontal plane trunk motion in children with CP compared to TD children [19], a compensation strategy previously reported to conserve lateral stability [17]. Malone et al. [19] and Coman et al. [33] also identified similar frontal plane trunk ROM between level and uneven surfaces. Conservation of lateral stability was demonstrated in other studies [22,26] by increasing step width to widen the BOS and increase dynamic stability on an uneven surface. Moreover, increased step width is a recognised strategy used by children with CP to increase stability when walking on level ground [15]; however, this modification is more likely when presented with an uneven surface.

Children with CP use conservative gait behaviours to compensate for instability caused by an uneven surface. Böhm et al. [22] also suggested that changes to specific gait pathologies including increased out-toeing combined with reduced ankle dorsiflexion may cause a fall due to the potential of accidental foot contact with raised sections of the uneven ground. Despite this, children with CP showed alternative compensations to increase foot clearance on uneven surfaces by increasing knee and hip flexion instead, both of which reduce risk of foot contact with the ground. Two studies suggested that increased knee and hip flexion is done to prioritize stability on the uneven surface at the detriment to conservation of energy [22,26]. Therefore, when fatigued, this less efficient gait pattern may become unobtainable and could increase fall risk.

The findings from this review suggest there may be links to increased fall risk in children with CP when walking on uneven surfaces, due to the nature of compensation strategies and the possible impact of fatigue on foot clearance. However, there are too few studies to provide a robust evidence base and, within these studies, none quantified fall occurrence or history of falls as an outcome measure. Further work needs to confirm whether evidenced gait compensations used by children with CP are enough to control instabilities and prevent a fall in real-world environments as well as confirm any contribution fatigue may have on fall risk. Additionally, research that defines the type of uneven surfaces that children with CP find most challenging may be helpful in creating a clearer picture of the causes of real-world falls.

(b) Gradient walking

Children with CP can modify their gait characteristics in a similar way to TD children to successfully maintain stability and safely negotiate inclines and declines. When walking uphill, children with CP reduced their walking speed compared to level walking [22–24,33,34], and exhibited increased hip flexion [23–25,34–36] and ankle dorsiflexion [24,25,34,35] in the same manner as TD children. Knee flexion, and forward trunk lean were also increased in children with CP to successfully ambulate the incline compared to level walking, but this increase was significantly greater for children with CP compared to TD children [23,25,34–36]. The greater adjustment in knee and trunk kinematics may possibly compensate for the increased difficulty walking on an incline and underlying muscle weakness in children with CP [1,23]. This is supported by the increase in step length on the affected limb identified by Camuncoli et al. [37] and Choi et al. [34], suggested to be a compensatory increase in work on the unaffected side in children with hemiplegia when walking uphill. Another important finding that may contribute to these greater adjustments is a reduced feeling of safety in children with CP when asked to ambulate on an incline. Topçuoğlu et al. [24] asked children about their feeling of safety, observed facial expressions, gaze direction and how vocal children were, which together indicated increased hesitancy when children with CP were faced with steep inclines.

During decline walking children with CP showed larger gait alterations to compensate for the challenging environment compared to TD children (e.g. reduced stride length, increased hip and trunk extension). Camuncoli et al. [37] specifically suggest a shorter stride length is used when walking downhill to increase stability. This may again be linked with reduced feeling of safety when faced with steep declines as suggested by Topçuoğlu et al. [24]. Two studies demonstrate contradictory knee and ankle mechanisms for walking downhill [23,24]. Stott et al. [23] identified increased knee flexion and ankle dorsiflexion at initial contact compared to TD children to control downward motion. Conversely, Topçuoğlu et al. [24] identified increased plantarflexion and knee extension at initial contact to control downward motion through lengthening of the body. Mélo et al. [36] also identified increased plantarflexion during downhill walking. These different strategies may be influenced by different measurement approaches. Stott et al. [23] used 2D analysis with digital video cameras compared to 3D motion capture used by both Topçuoğlu et al. [24] and Mélo et al. [36]. The accuracy of a video based 2D analysis is low compared to 3D analysis, due to increased measurement error during manual digitisation of video to calculate joint angles, shown here by large ranges in ankle dorsiflexion (-9° to 35°) and knee flexion (-3° to 32°) in children with CP [23]. Choi et al. [34] suggested another reason when they identified that children with hemiplegia show more plantarflexion on an unaffected limb when walking downhill. Stott et al. [23] only included children with diplegia (GFMCS II), whereas Topçuoğlu et al. [24] and Mélo et al. [36] included GMFCS I and were therefore higher functioning and potentially better able to achieve plantarflexion during the decline [34]. Choi et al. [34] discuss that these ankle mechanisms for negotiating downhill walking in children with CP should be further investigated. Nevertheless, all studies in this review demonstrate that children with CP can successfully negotiate declines.

Children with CP show the ability to successfully negotiate both inclines and declines, suggesting that this type of challenging environment may not be a significant contributor to real-world high fall occurrences, and that fall risk may be somewhat reduced by the cautious strategies identified in this review (Fig. 2a). Additional exploration of reasons for decreased feeling of safety on steep inclines and declines may offer deeper understanding of everyday experiences outside of such controlled environments, for example, if a reduced feeling of safety is linked to previous fall experiences or fear of falling.

(c) Obstacle crossing

Two studies suggest children with CP use compensatory gait mechanisms increased step width, increased foot clearance, and slower approach and crossing speed compared to TD children, to maintain stability in response to an obstacle [20,21]. However, slower crossing speed [20,21,33] and increased foot clearance [20,21], in combination with increased swing phase time [33], can be linked with longer single limb stance over an obstacle compared to level ground. Longer single limb stance time is inherently more unstable than double limb support due to reduced BOS and additional mechanisms needed to maintain balance [43]. Distance between the trailing limb and the obstacle was also reduced in children with CP compared to TD children [20,21]; however this was only significant for a higher obstacle, demonstrated by Law and Webb [21]. Children with CP also exhibited increased inter-trial variability of the path of the toe while stepping over the obstacle, which might suggest higher likelihood of tripping by contacting the obstacle; however, no falls were reported by either Malone et al. [20] or Law and Webb [21]. Malone et al. [20] and Coman et al. [33] identified increased anterior, lateral and rotational trunk motion in children with CP compared to TD children [20] and compared to level walking [33], which may lead to the COM moving outside the BOS more often, thus reducing stability and increasing fall risk. These trunk movements were suggested to be a result of an underlying lack of control of the trunk and pelvis segments together with compensatory movements for instabilities distally, such as at the ankle [20]. Lack of trunk and pelvis control and distal instabilities imply overall reduced stability compared to TD children over obstacles that may increase fall risk.

Law and Webb [21] identified reduced foot clearance in children with CP compared to TD children when presented with a higher obstacle, unlike the smaller obstacle in Malone et al. [20]. Perhaps during the more challenging (higher) obstacle, the compensatory increase in foot clearance is no longer obtainable due to lack of ROM or muscle strength that allows increased knee and hip flexion or is jeopardized to allow less time on single limb support. The reason for this difference warrants further investigation if high obstacles (and associated foot clearance or single limb support time) are to be considered as contributors to high fall risk in children with CP.

The high occurrence of stumbles identified by Bailes et al. [38] might suggest that children with CP demonstrate insufficient compensatory gait adjustments in response to crossing an obstacle, which could increase the risk of a fall. However, the lack of specificity of outcome measures within the SWOC test for determining where a stumble occurs makes it difficult to attribute any stumbles directly to crossing an obstacle. Malone et al. [20] additionally suggested that vision may be an important factor in stepping over an obstacle safely for children with CP [44], therefore indicating a possible direction for future work.

(d) Treadmill perturbations

Children were able to maintain stability in the one study that assessed treadmill perturbations, showing no falls and sufficient recovery strides [39]. Children with CP and TD children showed similar responses to a perturbation, including increased ankle dorsiflexion and knee flexion compared to walking without a perturbation. However, treadmill walking has previously shown differences to overground walking in TD children [45], and in children with CP [46]. Therefore, although limited evidence is presented here, it may be plausible that real-world perturbations do cause falls, however this treadmill task is not equivalent to a real-world perturbation that would cause a fall as is typically encountered day-to-day.

(e) Stair ambulation

Children with CP demonstrated slower walking speed on stairs compared to TD children and increased single limb stance time on the 'non-involved' (less affected) limb [40]. This may suggest a more cautious strategy to ambulate the increased challenge presented by stairs. Children with CP also demonstrated increased dorsiflexion, increased foot clearance and better foot placement with AFO use [40]. This, coupled with unlimited handrail use and the inclusion of only higher functioning children with CP (hemiplegia) likely reduced fall risk in this study. To determine any role that stairs may have on everyday fall occurrence, future work should explore the difficulty of stair negotiation across different levels of ambulatory function (GMFCS I to III) and with and without handrail use, since this is not always possible during real-world challenging environments.

### *4.3. Limitations*

A possible limitation of this review is the restricted age range in inclusion criteria. Six studies were excluded from this review because they included children with CP below 5 or above 18 years old [44,47–51]. Three of these studies documented occurrence of stumbles over either the SWOC [47,48] or a fixed obstacle [44]. These studies were excluded because participants were either younger [44,47,48,50] or older [49] than the inclusion criterion. The inclusion criterion in this review (5–18 years old) accounts for children with CP who fall more often compared to TD children (> 5 years old) [2,9] and those who experience most negative psycho-social consequences (9–17 years old) [4]. Therefore, findings of excluded studies may have been less applicable to fall occurrence and fall risk outcomes. For example, inclusion of younger children by Zipp and Winning [48], possibly led to an increased number of stumbles over the SWOC, in comparison to Bailes et al. [38], because very young children, regardless of CP, fall regularly [8]. Furthermore, the excluded studies show similar results to those discussed in this review, therefore, it is thought they would not add to the understanding of how challenging environments contribute to fall occurrence or fall risk in the real-world.

Another limitation of this review is the limited number of studies that quantify falls due to the primary focus of included studies on stability and fall avoidance rather than causes of falls. Reduced dynamic stability in any environment is an indicator of increased fall risk [11]. The inherent link between instability and fall risk suggests that studies included in this review are likely to provide the most relevant outcomes that could identify whether movement patterns of children with CP over challenging environments contribute to or compensate for increased fall risk. The studies included in this review provide a comprehensive overview of the factors that may contribute to falls (Figs. 2A and 2B).

### *4.4. Recommendations for future studies*

Future work could firstly consider more reporting of fall occurrences in the real-world, then how and why real-world falls occur. Children with CP do stumble when negotiating the SWOC [38], therefore a first step may be to isolate elements of the SWOC to understand over which obstacles or tasks stumbles are occurring. Future work could then consider exploring performance of children with CP on the SWOC test or similar tests that have applicability to real-world environments, such as an 'obstacles and curb test' [52], alongside a falls diary that children with CP and TD children can complete, to further investigate the link between challenging environments and falls.

Future investigation within each of the five challenging environments identified in this review should be undertaken to provide further insight into mechanisms of falls in children with CP. This coincides with a recent review suggesting more work is needed on understanding fall risk in children with CP and impact of challenging walking [15] and another examining gait adaptations in children with CP in some challenging environments [53]. Future investigations should specifically address hip and knee ROM, muscle strength, muscle weakness and single limb stance time when stepping over high obstacles (~20 % leg length), the impact of fatigue on sagittal ankle, knee and hip angles when walking over uneven surfaces, qualitative reasons for reduced feelings of safety during incline and decline walking and finally, fall risk gait characteristics (e.g. foot clearance, foot placement) during stair negotiation across different GMFCS levels, with and without handrails.

All included studies in this review had the limitation that they undertook measurements within a controlled laboratory environment. Previous work suggests that children show improved gait characteristics within a clinical setting [54], therefore accurate reflection of how gait may change to contribute to or compensate for instability in challenging environments from this review may not reflect real-world places where falls occur. Investigation is required focusing on real-world challenging environments in which falls do occur outside the laboratory, informed by lived experiences of children with CP, to assess specific compensatory and contributory mechanisms of falls within those real-world places. This would extend knowledge beyond the current literature presented in this review.

Determining where falls occur, the influence of real-world environments and the impact of sensory challenges are important considerations for future falls research in children with CP. No studies in this review explored the impact that sensory or cognitive factors may have on instability within challenging environments. Reduced vision or cognitive ability, vestibular deficits, reduced concentration or environmental distractions, could contribute to increased fall risk or balance deficits for children with CP when walking in challenging environments [55]. Visual factors affecting falls were suggested by Malone et al. [20] as an avenue for future work during obstacle crossing. Furthermore, Sansare et al. [55] recently confirmed that visual information is important for maintaining balance and deserves more attention when planning treatment and interventions for fall prevention in children and adolescents with CP. Additionally, UK guidelines for clinical movement analysis, which most commonly informs treatment for children with CP explicitly states that environments should be non-distracting, emphasising the role distractions may play on gait and walking behaviour in children [56].

To find out what makes an environment challenging and likely to lead to a fall, exploration first needs to identify where real-world falls occur, and the multi-faceted reasons why falls occur. This could be achieved by learning from the insights and lived experiences of children with CP and their families about falls in their everyday environments or by monitoring behaviour in the real-world during tasks like those discussed in this review.

## 5. Conclusion

This review sought to systematically synthesise literature on whether challenging environments impact falls in children with CP. Existing knowledge stating that children with CP fall often is extended in this review, highlighting that challenging environments are a cause of near-falls and children with CP respond by utilising compensatory stability strategies. However, the link between these gait adaptations and fall occurrence in challenging environments has not been demonstrated. Findings from this review cannot confirm which challenging environments may contribute to high fall occurrence in the real-world. However, obstacle crossing, uneven surfaces, steep declines and stair ambulation may warrant further detailed investigation and specific recommendations have been provided. The 16 studies included in this review highlight a broader lack of investigation into falls and fall-risk in real-world environments for children with CP, given the limited evidence available. Nevertheless, this review provides a comprehensive overview of factors that may contribute to falls, while also highlighting key areas for investigation in order to understand how challenging environments contribute to falls in the real-world for children with CP. Specific recommendations of how future work might address this are offered within this review, that are essential to bring us closer to understanding falls, informing fall prevention and reducing the negative consequences of falls for children with CP.

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## Additional information

This systematic review protocol was registered with PROSPERO: https://www.crd.york.ac.uk/prospero/display_record.php?RecordID= 290456. The data extraction sheet aligned with this review is freely available to the reader on request.

## CRediT authorship contribution statement

**Bernie Carter:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Richard John Foster:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gabor Barton:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **David Wright:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Rebecca Walker:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Thomas O′Brien:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

## Declaration of Competing Interest

The authors declare no conflicting interests.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.01.008.

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